

# Timing in the absence of a clock reset

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**Prominent models of time perception assume a reset of the timing mechanism with an explicit onset of the interval to be timed. Here we investigated the accuracy and precision of temporal estimations when the duration does not have such an explicit onset. Participants were tracking a disc moving on a circular path with varying speeds, and estimated the duration of one full revolution before the stimulus stopped. The onset of that revolution was either cued (explicit), or undetermined until the stimulus stopped (implicit). Reproduced duration was overestimated for short and underestimated for long durations, and variability of the estimates scaled with the duration in both temporal conditions. However, the bias was more pronounced in the implicit condition. In addition, if the stimulus path was partially occluded, duration of the occluded motion was correctly estimated. In a second experiment, we compared the precision in the explicit and implicit conditions by asking participants to discriminate the duration of one revolution before the stimulus stopped to that of a static stimulus presentation in a forced-choice task. Sensitivity of discrimination was worse in the implicit onset condition, but surprisingly, still comparable to the explicit condition. In summary, the estimates follow principles described in prospective timing paradigms, although not knowing beforehand when to start timing decreases sensitivity of temporal estimations. Since in naturalistic contexts, we often do not know in advance which durations might be relevant to estimate, the simple task presented here could become a valuable tool for testing models of temporal estimation.**

## Introduction

The most influential models of time perception are inspired by a clock metaphor and propose a dedicated clock mechanism to account for human and animal

estimation of time (for a review see Gorea, 2011; Gu, van Rijn, & Meck, 2015; Addyman, French, & Thomas, 2016; Wearden, 2016). One common attribute of different dedicated time models is the notion of mandatory resetting of the clock. For example, in pacemaker-accumulator models, timing of a duration is achieved by accumulating (and counting) events generated by a pacemaker. In order to estimate duration of an interval, a “reset” of the timing mechanism at the onset of the interval is required. This is achieved by opening and closing a switch between the pacemaker and the accumulator (Treisman, 1963; Gibbon, 1977; Allan, 1979; Miall, 1989; Allman, Teki, Griffiths, & Meck, 2014). These models were mostly conceptualized and validated by means of prospective duration estimation tasks. In these tasks, participants are instructed to begin and end temporal estimation with an onset and offset of the stimulus. This approach had a great success in describing some properties of human and animal temporal estimation, such as the so-called “scalar property of timing” and Vierordt’s law. The former property refers to the scaling of the variability of temporal estimates with estimated duration (Church, 1984; Gibbon, 1977; Mattel & Meck, 2004; Allman et al., 2014, although see Lewis & Miall, 2009). Vierordt’s law refers to a tendency of temporal estimations to regress to the mean (overestimation of short and underestimation of long durations; Lejeune & Wearden, 2009; Jazayeri & Shadlen, 2010; Mamassian & Landy, 2010; Wearden, 2016), and it has been shown that this regression depends on the uncertainty of temporal estimates (Jazayeri & Shadlen, 2010). In spite of its popularity, it is fair to say that the dominant paradigm of prospective duration estimation narrowed the scope of the temporal phenomena being investigated. Importantly, these models cannot explain estimation of time when no clear onset of the duration to be timed is provided.

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In our daily life, we are sometimes exposed to events that arrive to our senses at unexpected times and that last for variable durations. Since we do not always know beforehand which events could be relevant for us and which durations we would need to estimate, humans must be able to estimate durations of past events even when they were not explicitly timed while unfolding. In the literature, such mechanisms have been referred to as retrospective, in contrast to prospective timing (Fraisse, 1963; Fraisse, 1984; Poynter, 1989; Zakay & Block, 2004; Wearden, 2016). The main characteristics of retrospective timing estimation are that one does not know beforehand that duration of a particular interval will be estimated, and so no attention is directed to time while the event is taking place (Grondin, 2010; Block & Grondin, 2014; Wearden, 2016).

A timing mechanism that can explain retrospective time estimation has been the focus of recent computational models. These models propose that reconstructing history of neural activation or memory trace is employed for estimation of time (Staddon & Higa, 1999; Staddon, 2005; Shankar & Howard, 2010; French, Addyman, Mareschal, & Thomas, 2014; Addyman et al., 2016). This is a formalization of older ideas about the close relationship between memory about events or changes, and time estimation (Fraisse, 1963; Block, 1978; Poynter, 1989; Liverence & Scholl, 2012). The strength of these models is that they do not need any assumption about an explicit beginning of timing corresponding to the onset of an event. Furthermore, these frameworks unify prospective and retrospective time estimation (Addyman et al., 2016).

However, behavioral evidence for timing without clock reset is scarce (Block & Zakay, 1997; Wearden, 2016). In retrospective paradigms participants are asked to estimate the duration of an event only after the event has elapsed. In order not to direct participants to pay attention to passage of time and start timing at the beginning of the event, each participant can be asked to report duration only once per experiment, which makes these paradigms very costly for the experimenter.

Previous studies have shown that retrospective estimates of time tend to be shorter and more variable than prospective estimates, with variability growing faster with duration (Unrug-Neervoort, Kaiser, Coenen, & van Luitelaar, 1991; Block & Zakay, 1997; although see Boltz, 2005). Moreover, despite the fact that models usually explain perceived duration in the milliseconds to seconds range, previous work with retrospective time estimation targeted mostly much longer durations (tens of seconds to minutes) using more cognitive than perceptual tasks and complex stimuli (Grondin, 2010).

In the work reported here, we address the notion of timing a visual event without an explicit clock reset by introducing a novel paradigm that allows us to compare

time estimation with and without a cue for “resetting” the clock. We ask participants to estimate the duration of an event linked to a moving stimulus. The stimulus is moving along a circular path with varying speed and the task is to estimate the duration of one full revolution just before the stimulus stopped. We call this revolution, and corresponding duration, “revolution (duration) to be estimated.” In the “explicit onset” condition, the stimulus completes only one revolution, and participants estimate the duration from the beginning to the end of the trial. In the critical “implicit onset” condition, the stimulus moves for a variable duration before stopping. Importantly, in this latter condition, participants do not know when the revolution to be estimated would start. Only when the stimulus stops does the participant know the duration to be estimated. The position where the stimulus stops indicates both where and when the revolution to be estimated started, thus revealing the temporal interval between that position and the moment when the stimulus was on that same position one revolution back.

In the implicit onset condition, there is no explicit cue for resetting the clock. However, participants were aware that they are estimating the duration on each trial, and inevitably attended to time (Grondin, 2010; Block & Grondin, 2014; Wearden, 2016). Therefore, our task is arguably “prospective” because participants were prepared to estimate time, but also “retrospective” because they needed to go back in time to estimate when an event occurred. Instead of following this terminology found in the literature, we choose a more neutral way to refer to the two tasks (“implicit” and “explicit”). That being said, the task presented here still enables us to address the question of timing when there is no explicit cue to initialize a clock.

## Experiment 1A

The purpose of the first experiment was to address two issues. First, we aimed to investigate how well humans can estimate durations in the condition where no explicit onset of the duration is shown. We compared performance in this novel task to that obtained with a simple prospective duration reproduction task.

In order to understand better how the duration of a moving object is computed, we sometimes occluded part of the object trajectory. Humans are very good at extrapolating motion of objects behind occlusions, and at least partly, rely on the same mechanisms as those used when tracking visible motion (Olson, Gatenby, Leung, Skudlarski, & Gore, 2004; Graf, Warren, & Maloney, 2005; Makin, Poliakoff, & El-Deredy, 2009; Battaglini, Campana, & Casco, 2013; Battaglini & Casco, 2016). However, extrapolating occluded motion

leads to timing errors, such that the estimated time of an object motion behind occlusions is typically overestimated, and this effect is larger for slower speeds (Yakimoff, Mateeff, Ehrenstein, & Hohnsbein, 1993; Sokolov & Pavlova, 2003; De Freitas, Myras, & Nobre, 2016). In the second part of the experiment we investigated whether temporal errors due to occlusion affect estimated duration of the moving object.

## Material and methods

### Stimuli and apparatus

The stimulus was a red disc, size  $0.6^\circ$ , rotating along a white circular path, with a radius of  $3.7^\circ$ . The background was gray, and the occluder was dark gray. A white fixation dot (size  $0.6^\circ$ ) was presented at the center of the screen throughout the duration of a trial. In order to make the occluded and not occluded conditions visually similar to each other, an occluder was present in all conditions. In the occluded condition, the occluder was presented on top of the stimulus path, occluding the trajectory of the stimulus (as if the disc was going under a tunnel). In the not-occluded condition, it was presented behind the path and the stimulus moved over it (as if the disc were going over a bridge).

The experiment was conducted in a dimly lit room. Experiments were created using Matlab R2016a and Psychtoolbox-3 (Brainard, 1997; Pelli, 1997; Kleiner et al., 2007) running on a MAC Pro Quadro-Core Intel Xeon (Apple Inc., Cupertino, CA), with OSX 10.5.8. Stimuli were presented on a LCD flat screen (ViewSonic V3D245; ViewSonic Corporation, Brea, CA), with diagonal 24-in., resolution  $1,920 \times 1,080$  pixels, and refresh rate 60 Hz. The viewing distance was 50 cm.

The analysis of the data was conducted in R Studio environment (RDevelopment C.O.R.E., 2012), using packages “lme4” (Bates et al., 2014) and “lmerTest” (Kuznetsova, Brockhoff, & Christensen, 2015) for mixed-effect regression analysis, “Quickpsy” package (Linares & López-Moliner, 2016) for fitting psychophysics data, and “Bayes factor” (Morey, Rouder, Jamil, & Morey, 2015) for comparing likelihood of regression models.

### Participants

Eight human participants (including two males, mean age 23 years) performed Experiment 1. All participants but one (the first author) were naive to the purpose of the study and gave written informed consent and received monetary compensation. The experiment was conducted in agreement with the Declaration of Helsinki and local ethics regulations.

### Procedure

On each trial, participants were tracking the red disc that moved along the circular path. They were asked to reproduce the duration of one full revolution of the disc just before it stopped moving (revolution to be estimated) by pressing a key on a keyboard. The task was to match the temporal interval between the key press and the disc stop to the interval between the disc stop and the time the disc was at that same position in the previous revolution.

A trial started with the presentation of the path for the disc and the fixation point (Figure 1). Participants were instructed to fixate at the fixation point at the center of the screen. After 200 ms, the disc appeared and started moving in the counterclockwise direction. The duration of the movement depended on the condition and the interval duration tested. In the explicit onset condition, the trial consisted of only one revolution, and participants were instructed to estimate and reproduce how long the disc was moving, from the beginning to the end of the movement. In the implicit onset condition, the moving disc made more than one revolution. When the disk stopped, participants were asked to reproduce the duration of the revolution to be estimated, marked by the ending position of the disk (how long it took for the disc to get to this position relative to the previous time it was there). In other words, participants did not know when/where the revolution to be estimated started until the end of the trial. In the experiment, stimuli started moving from the same position but stopped at different positions along the path. The two conditions were tested in separate blocks. We will refer to the two conditions as explicit onset if the onset of the duration to be estimated was known, and implicit onset if no explicit onset of the duration was presented. A video of a single trial can be downloaded from online version of the article (Supplementary Movie S1).

Speeds were chosen from the range 0.2–1.2 revolutions per second, randomly for each trial. In the revolution to be estimated, the speed was chosen to correspond to one of five interval durations. Durations to be reproduced were logarithmically equally spaced intervals, from 1.1 to 3.5 s. We also introduced filler trials, with random durations (5% of trials), in order to make it more difficult for participants to learn and predict durations. In the implicit onset condition, the disc moved on average 0.838 s ( $SD = 1.02$  s) before making the revolution to be estimated. The two conditions (implicit and explicit onset) were tested in separate blocks. There were 16 repetitions of each of the durations. Before the beginning of the experiment, there were 30 practice trials with feedback. The experiment lasted about 2.5 hr and participants completed it in two blocks on separate days.

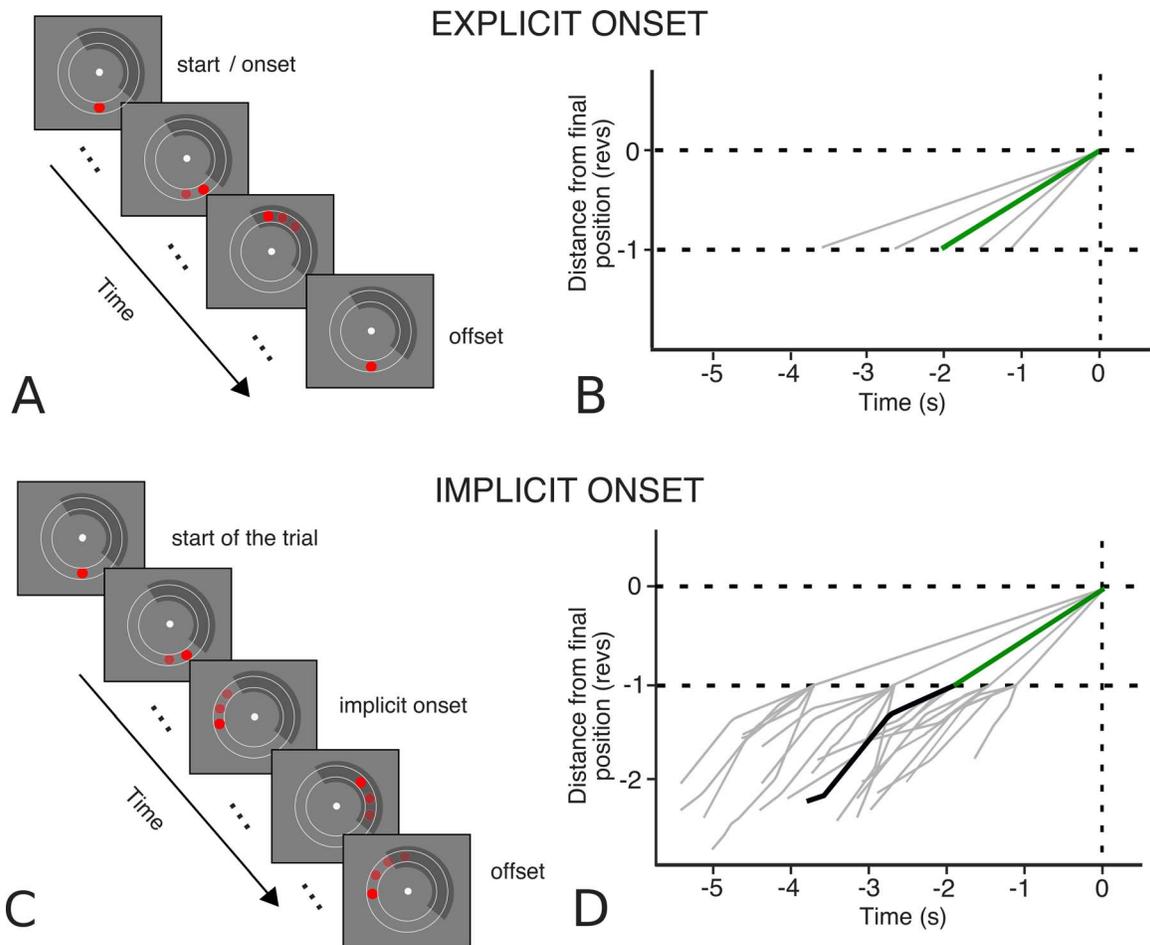


Figure 1. Illustration of the stimulus sequence in the explicit (A–B) and implicit (C–D) conditions. (A) The stimulus started moving in counterclockwise direction with a constant speed. The stimulus made only one revolution, and participants were asked to reproduce the duration from beginning to the end of the movement. (B) Change of the stimulus position as a function of time in the explicit onset condition. Lines correspond to five different durations (the middle duration is depicted in green for comparison with the conditions in the implicit onset task). In this condition, the stimulus always made only one revolution and started and ended the movement at the same position on the screen. (C) In the implicit onset condition, the stimulus started moving from the same position as in the explicit onset condition (6 o'clock), but because it made more than one revolution, its final position was different from trial to trial. Participants did not know where or when the stimulus would stop, so they had to attend to the moving stimulus throughout the trial. When stimulus stopped, they were asked to reproduce the duration of the one revolution before it stopped. (D) The position of the stimulus on the circular path in the implicit condition is plotted against the time from the beginning of the trial. Curves illustrate stimulus displacement for the five durations. For example, the black-green curve is illustrating one trial where participants were asked to estimate 2-s duration. The stimulus started moving with changing speeds for a variable duration (black part of the curve), before making the final revolution (green). When the stimulus stopped, participants estimated the temporal interval of the one revolution back (temporal interval corresponding to the spatial interval between positions  $-1$  and  $0$  on the  $y$ -axis of the figure). Position and time are aligned with respect to the offset of the disc that defined the duration participants were asked to reproduce. For simplicity only nonoccluded trials are shown here (stimulus path was partially occluded in 50% of trials), see Figure 2 for occluded conditions.

### Occlusion

In order to test whether the reduction of visual information affects the estimation of time, we partially occluded the stimulus path in half of the trials. In the occluded trials, one third of the disc path was occluded with a single occluder and the location of the occluder was varied from trial to trial. The disc never finished its

movement behind the occluder. On 12% of the trials, the disc changed its speed behind the occluder, resulting in a conflict with temporal expectation (an example trial is shown in Figure 2B). The reason for including these trials was to encourage participants to attend to time rather than position or speed. These few trials were not analyzed further.

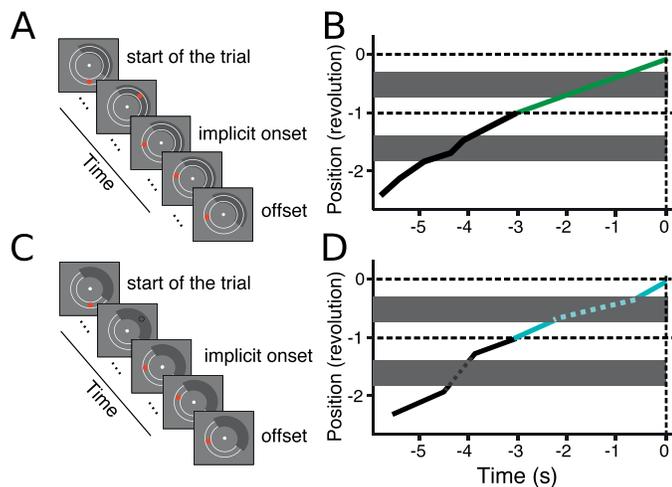


Figure 2. Illustration of the two trials in the not occluded (A–B) and occluded (C–D) conditions. On Panels A and C, stimulus sequence for not occluded (A) and occluded (C) are shown. On Panels B and D, not occluded and occluded trials are shown. The duration to be estimated is the same in the two trials, but in the trial shown on Panel B, the stimulus is moving at constant speed, and on Panel D, it changes speed behind the occluder.

## Results

### Temporal estimation with and without the explicit onset of duration

In Figure 3, reproduced duration is plotted against presented duration for the two temporal conditions, separately for the occluded and not-occluded trials. To estimate the accuracy of reproduced durations in the two tasks, for each presented duration, we calculated the reproduction error as the mean difference between reproduced and presented duration.

As shown in Figures 3 and 4, participants were overestimating durations of short intervals and underestimating durations of long intervals. The effect was present in both conditions, but it was smaller for the explicit onset condition. We quantified the effect with a linear mixed-effect model, using

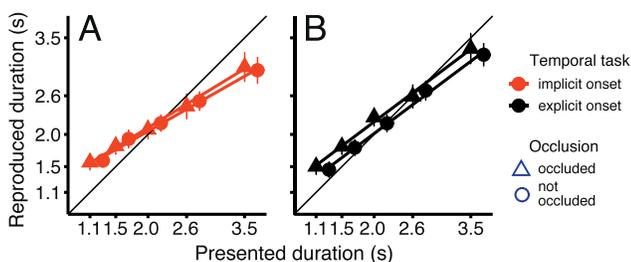


Figure 3. Reproduced against presented duration for the two temporal tasks (implicit in red on Panel A and explicit in black, Panel B). The two occlusion conditions are shown with different marker shapes.

the logarithm of presented duration and temporal task (explicit or implicit onset) as predictors and reproduction errors as the criterion variable. We included participants as a random factor to account for additional variability. We observed the effect of presented duration ( $b = -2.006$ ,  $SE = 0.1$ ,  $t = -18.315$ ,  $p < 0.01$ ), the temporal task ( $b = -0.226$ ,  $SE = 0.053$ ,  $t = -4.240$ ,  $p < 0.01$ ) and their interaction ( $b = 0.823$ ,  $SE = 0.150$ ,  $t = 5.48$ ,  $p < 0.01$ ). Excluding the interaction of the two predictors decreased the goodness-of-fit, quantified by comparing the log-likelihoods of the two models by means of chi-square analysis ( $\chi^2(1) = 24.422$ ,  $p < 0.01$ ). This analysis confirmed that the slopes were different from zero, and different between the two temporal conditions (when analyzed separately,  $b = -2.010$ ,  $SE = 0.100$  for explicit and  $b = -1.16$ ,  $SE = 0.107$  for implicit onset conditions).

We assessed the scalar property of time estimation by plotting variability of the estimation (standard deviation) of the reproduced duration as a function of the presented duration (Figure 4B). Variability in both conditions scaled linearly with presented duration. To quantify the effect, we conducted a linear mixed model, with the presented duration and the temporal task as predictors and standard deviation of reproduced duration as the criterion, with subjects as a random factor (intercept only). We observed an effect of presented duration on the standard deviation of reproduced duration ( $b = 0.085$ ,  $SE = 0.01$ ,  $t = 6.198$ ,  $p < 0.01$ ). Even though Figure 2B presents a trend for greater variability in the implicit onset condition, coefficients for the temporal condition and interaction were not significantly different from zero ( $b = 0.04$ ,  $SE = 0.045$ ,  $t = 0.099$ ,  $p = 0.921$ , and  $b = -0.02$ ,  $SE = 0.02$ ,  $t = -1.02$ ,  $p = 0.308$ ).

### Temporal estimation is not affected by occlusion

To test whether a reduction of visual information by occlusion affects the estimated duration, we introduced an occluder on the stimulus path on half of the trials. In Figure 5, we contrast the errors in the occluded and not-occluded conditions by comparing the mean error per participant for the five presented durations and the two temporal conditions. Reproduction errors were strongly correlated (Spearman's rank correlation  $\rho = 0.835$ ,  $p < 0.01$ ).

To further quantify the effect of the occlusion, we fitted the data with a linear mixed-effect model, using temporal errors as the criterion, and the logarithm of presented duration, the two temporal conditions (explicit and implicit onset) and the two occlusion conditions as predictors. The effect of the logarithm of presented duration ( $b = -1.937$ ,  $SE = 0.08$ ,  $t = -23.795$ ,  $p < 0.01$ ), temporal task ( $b = -0.160$ ,  $SE =$

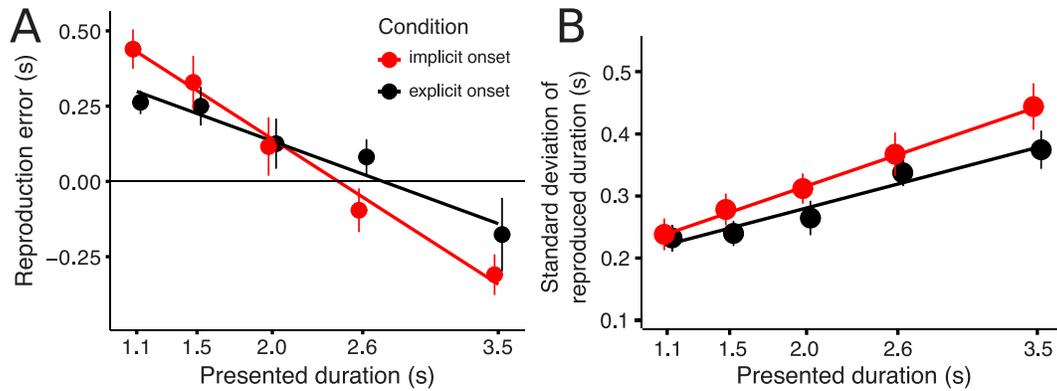


Figure 4. Bias and variability of temporal estimates in implicit (red) and explicit (black) onset conditions. (A) Mean errors in reproduction averaged across participants are plotted against presented durations. Positive errors indicate overestimation, and negative errors, underestimation of durations. Participants overestimated short and underestimated long durations. (B) Scaling of variability (averaged standard deviation across subjects) of reproduced duration as a function of presented duration. Variability increases linearly with presented duration. Error bars are standard errors of the mean.

0.04,  $t = -4.042$ ,  $p < 0.01$ ) and the interaction of the presented duration with the temporal task ( $b = 0.772$ ,  $SE = 0.114$ ,  $t = 6.719$ ,  $p < 0.01$ ) were significant predictors. However, there was no effect of occlusion ( $b = -0.01$ ,  $SE = 0.02$ ,  $t = -0.5$ ,  $p = 0.617$ ). We quantified the evidence for no effect of occlusion by means of Bayes factor (BF). We compared the likelihood of this model with an alternative model that did not include occlusion as a predictor. The Bayes factor reached 19.76, a value considered as strong evidence that performance with and without occlusion were not different (Masson, 2011; Jarosz & Wiley, 2014).

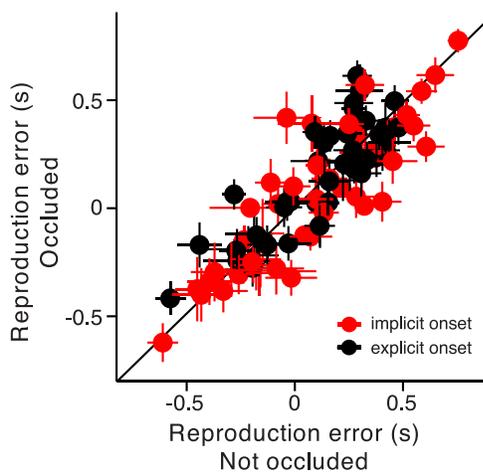


Figure 5. Reproduction errors in the not-occluded condition, contrasted against errors in the occluded condition. Each symbol is the mean of a different participant in one of the five stimulus durations. Different colors correspond to implicit (red) and explicit (black) onset conditions. Error bars are standard errors of the mean.

## Experiment 1B

The aim of Experiment 1B was to address two issues. First, in the main conditions of Experiment 1A, duration to be estimated coincided with a change of speed. Therefore, participants could try to use that information when reproducing durations. In Experiment 1B, speed was not constant in the full revolution just before the stimulus stopped. Additionally, durations to be estimated were not constrained to a set of five values, and instead were in the range from 0.7 to 4.6 s (actual values were determined by the number of different speeds and the path length the stimulus was travelling in the full revolution before it stopped). Second, we tested two implicit onset conditions. In the first, the speed change coincided with the implicit onset of the duration to be estimated, and in the second, the stimulus was moving for more than one full revolution with the same speed before stopping.

## Material and methods

Stimuli and apparatus were identical to those in Experiment 1A.

### Participants

Eight human participants (two males, mean age 25.4 years) performed Experiment 1B. All participants but the first author were naive to the purpose of the study, signed informed consent and received monetary compensation. The experiment was conducted in agreement with the Declaration of Helsinki and local ethics regulations.

## Procedure

The procedure was similar to the procedure of Experiment 1A. The only difference was that participants completed three separate blocks, two implicit onset (speed change or no speed change) and one explicit onset (one revolution) conditions. The order of the blocks was counterbalanced across participants. There were 80 repetitions per condition. Before an experimental block, participants performed 30 trials of practice with feedback.

## Results

To summarize the performance we first binned presented duration in five equally sized bins. For each bin and condition we calculated mean reproduced duration, shown on Figure 6.

As in Experiment 1A, we observed that reproduced durations regressed to the mean presented duration. Also, the effect was larger for the two implicit onset conditions. To quantify the effect we performed a linear mixed effect model, with presented duration and the three conditions as predictors, and reproduced duration as criterion variable. We included participants as a random factor to account for variability on individual level.

Not surprisingly, reproduced duration scaled linearly with presented duration ( $b = 0.342$ ,  $SE = 0.021$ ,  $t = 16.08$ ,  $p < 0.01$ ). Importantly, we observed an interaction between presented duration and temporal condition, in the sense that the effect of presented duration was larger for explicit onset relative to the implicit onset with speed change condition ( $b = 0.120$ ,  $SE = 0.040$ ,  $t = 3.027$ ,  $p < 0.01$ ). Since the presented durations were not constrained, instead of looking at standard deviation of reproduced duration we cannot assess the variability of reproduced duration as in Experiment 1A.

## Discussion of Experiments 1A and 1B

In the first experiment, we asked participants to reproduce the duration of the full revolution before a stimulus stopped moving along a circular path. The onset of the revolution was not always cued: In an implicit onset condition, it was only available to participants retrospectively. We compared performance in this condition to that obtained in a control condition in which the stimulus always made only one revolution.

We found that durations were overestimated for short and underestimated for long temporal intervals.

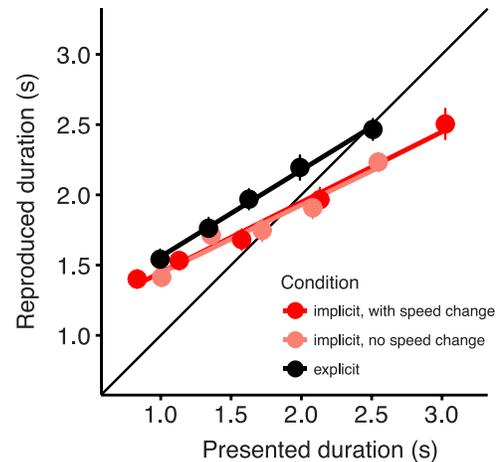


Figure 6. Bias of temporal estimates in implicit (red and light red) and explicit (black) onset conditions. Mean reproduced duration in reproduction averaged across participants is plotted against binned presented duration. The three temporal conditions are color coded. Errors bars indicate the standard error of the mean.

In addition, we found a linear relationship between presented durations and variability of reproduction, which is commonly referred to as scalar variability of timing (Bangert, Reuter-Lorenz, & Seidler, 2011; Allman et al., 2014). In the present experiment, the rate at which variability of the estimation increased as a function of presented durations was not different between the two conditions.

Finally, there was no effect of the occluder on the performance, and the temporal estimates were unaffected by occlusion of a part of the stimulus trajectory. This finding suggests that even though extrapolation of occluded motion can be biased (Yakimoff et al., 1993; Sokolov & Pavlova, 2003; De Freitas et al., 2016), humans can successfully overcome these biases when estimating the overall duration of an event.

We observed an overestimation of short and underestimation of long durations (Figure 4A), known as Vierordt's law (Wearden, 2016) or regression to the mean (Jazayeri & Shadlen, 2010; Allman et al., 2014). Even though the effect was shown to depend on the temporal context and uncertainty of temporal estimates (Jazayeri & Shadlen, 2010), we did not observe significant differences in variability of the temporal estimates. On the other hand, since we used a reproduction task to assess temporal estimates, final variability in estimates included both uncertainties of temporal estimation as well as motor noise.

In Experiment 1B, we replicated results from Experiment 1A. We again observed an overestimation of short and underestimation of longer durations for all three conditions, and an interaction of the effect with temporal condition. Additionally, we showed this to be the case even with variable speed in the one revolution

before the end of the motion and for a greater number of durations to be estimated. Finally, whether or not implicit onset coincided with change in speed had no effect on estimated duration.

We conducted another experiment to estimate the uncertainty of temporal estimation in the two tasks. In the following experiment, we asked participants to compare the duration of a moving stimulus with that of a static one. By pressing participants to make a forced-choice judgment, we eliminated possible biases coming from the reproduction task, and the sensitivity of this paradigm gave us a better estimate of the uncertainty underlying the temporal tasks.

## Experiment 2

In the first experiment, we showed that humans could estimate the duration of an event even when there was no explicitly cued onset of that event. Estimations in this implicit onset condition were nonetheless less accurate than more common prospective ones.

In the second experiment, we tested the performance for explicit and implicit onset time estimation in a different task. We presented two stimuli sequentially, a dynamic and a static disc, and participants were asked to compare the durations of the two stimuli. By using binary responses to assess perceived duration, we eliminated possible biases coming from response times and motor noise. Also, information about sensitivity of discrimination in different tasks provided us with additional insight into the way humans estimate time with and without explicitly cued onset of a duration. A final motivation for the present experiment was to test our experimental paradigm in a different task.

The dynamic disc was moving on a circular path, as in Experiment 1. It was followed or preceded by the presentation of a static disc, and on each trial participants compared the time it took the moving disc to make one full revolution before it stopped (revolution to be estimated) to the duration that the static disc was presented on the screen. We again contrasted performance in a condition where the dynamic disc made only one revolution (explicit onset) with the condition where no explicitly cued onset of the revolution to be estimated was presented (implicit onset). Additionally, we introduced another explicit onset condition, where the disc made more than one revolution, but a brief abrupt stopping of the disc cued onset of the revolution to be estimated (in the remainder of the text we will use “one revolution onset” and “cued onset” to differentiate these two conditions). We introduced the cued onset condition in order to check whether exposure to irrelevant motion and varying speeds in the implicit onset condition affected

temporal estimates and exaggerated differences between the two conditions.

## Material and methods

Stimuli and apparatus were identical to those in the previous experiment.

### Participants

Eight participants (including three males, mean age 25) completed the experiment. One participant failed to understand the task so an additional participant was recruited. The experiment was conducted in agreement with the Declaration of Helsinki and local ethics regulations and all participants gave informed consent.

### Procedure

We used a one-interval two-alternative forced-choice paradigm and asked participants to compare durations of the dynamic disc to that of the static one. On each trial, the dynamic and static discs were presented sequentially (Figure 6). The task was to compare the duration of the full revolution of the dynamic disc before stimulus stopped (revolution to be estimated) to the duration of the static disc presentation, by giving a response on the keyboard (choosing between moving or static disc the one that appeared to last longer).

The dynamic disc was identical to those in used in Experiment 1, but the duration of the revolution to be estimated was fixed to 1.1 s (instead of five durations from 1.1 to 3.5 s tested in the first experiment). We also decreased the duration of the movement before the revolution to be estimated to an average of 0.4 s ( $SD = 0.12$  s), since participants had to sequentially compare the two durations and a long interval between the two would introduce additional memory noise. The static disc was the same red disc, which stayed on the screen for a variable duration. We varied the duration of the static disc in five logarithmically equally spaced steps, from 0.4 to 3 s. To mark the offset of both static and moving durations more clearly, stimuli changed their color to blue before disappearing. We used the method of constant stimuli, and the order of presentation was randomized. Each stimulus duration was probed 30 times. The onset condition was tested in two blocks, one in which the onset of the targeted revolution was cued by stopping of the stimulus for 300 ms, and the other where the moving stimulus made only one revolution (Figure 7C and D). The total duration of the experiment was 1.5 hr, with two breaks in each block. Before the beginning of the experiment, participants completed 30 practice trials with feedback, but no feedback was provided during the actual experiment.

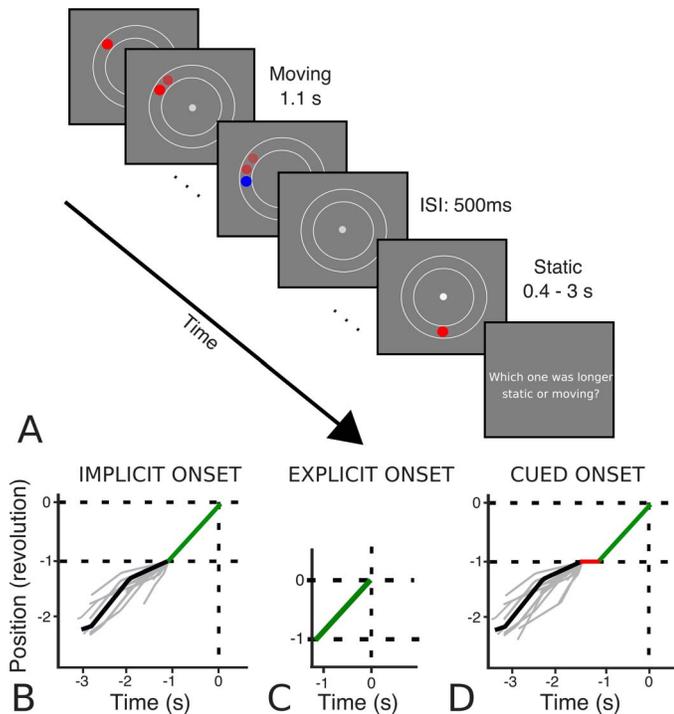


Figure 7. Illustration of one trial in Experiment 2. (A) Participants compared the duration of the targeted revolution of the moving disc with the duration of the static one. (B–D) Illustrations of trials in the implicit and the two explicit onset conditions. In the implicit onset condition (A), the stimulus moved with different speed for a variable time, before making the targeted revolution. In the one-revolution onset condition (C), the stimulus made a single revolution. In the cued onset condition (D), the stimulus moved for a certain time (black), then stopped for 300 ms to mark the onset (red), and then made the targeted revolution (green).

## Results

To estimate how well humans can perceive the duration of an event that has no clear onset, we fitted the proportion of responses the static stimulus was judged to be longer as a function of the static stimulus duration with a cumulative normal distribution (Figure 8A). For each participant and condition (implicit onset and two explicit onset conditions), we calculated the point of subjective equality and the discrimination sensitivity. The point of subjective equality was the duration that led to 50% probability of judgments either “shorter” or “longer” than the standard, and the sensitivity was taken to be the inverse of the standard deviation of the fitted normal distribution. Sensitivity of the duration discrimination between the static and the moving stimuli is shown on Figure 5B. There was a trend of a decrease in sensitivity, where the condition with one revolution having the largest and the implicit onset condition the smallest sensitivity. To compare sensitivities in the three conditions, we conducted

permutation tests for each condition against the other two conditions (three comparisons in total). We permuted the data from a pair of conditions for each participant 10,000 times and analyzed the distribution of differences in two sensitivities, randomly assigned to one of the two conditions. We analyzed the data of seven participants, excluding one participant whose sensitivity in the one-revolution onset condition was outside the 1.5 interquartile range. Permutation tests showed that sensitivity was indeed significantly larger in the one-revolution onset compared to the implicit onset condition ( $p = 0.02$ ), but the other two comparisons were not significantly different from the distribution of random variations (two explicit onset conditions:  $p = 0.1$  and implicit onset and cued onset  $p = 0.096$ ).

We observed considerable variability in the perceived duration of the moving stimulus for the implicit onset and the cued onset condition. The three permutation tests showed that the actual observed differences in each pair were not different from random differences obtained by permutations (the probability that observed differences were due to random variations was 0.71 for the difference between two explicit onset conditions, 0.755 for one revolution onset and implicit onset, and 0.794 for the cued onset and implicit onset conditions).

To investigate whether the order of stimuli presentation affected performance, we analyzed the data separately for the two ordering presentations (static stimulus presented first or second). As shown in Figure 9, performance was better if the static stimulus was presented after the moving one. This was true for the implicit onset (permutation test for the difference,  $p = 0.007$ ) and cue onset conditions ( $p = 0.008$ ), but it did not reach significance for the one-revolution onset condition (0.087).

## Discussion

In the second experiment, we asked participants to compare the duration of one revolution of a dynamic disc before the stimulus stopped moving (revolution to be estimated) to that of a static disc. We compared performance across three conditions, two explicit onset (one-revolution onset and cued onset) conditions and one implicit onset condition. We found no systematic biases in perceived duration for the three conditions. However, sensitivity was greater in the one-revolution onset condition, indicating that participants could discriminate durations better when the onset of the duration to be estimated was known. Interestingly, the condition in which the onset of the revolution to be estimated was cued by a brief stopping of the stimulus was not better than the implicit onset condition and not

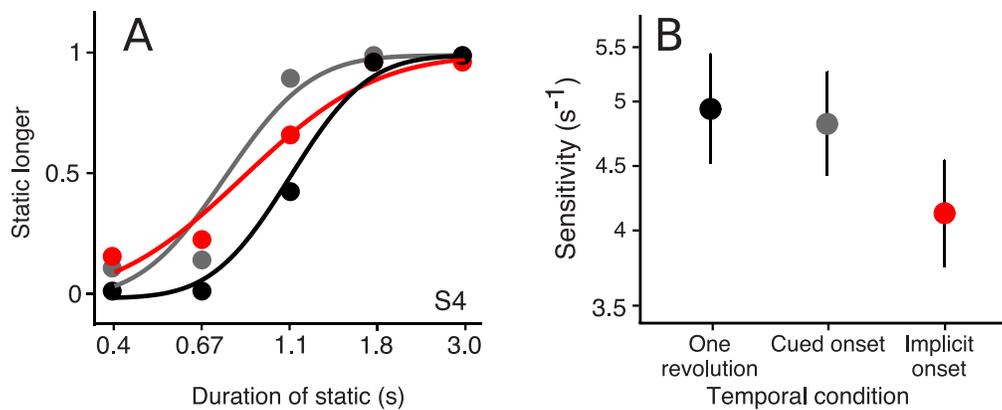


Figure 8. Performance in Experiment 2. (A) Psychometric function of one participant. The proportion of judgments for “static longer” is plotted against duration of the static stimulus on a logarithmic scale. (B) Sensitivities (inverse of slopes of the curves on Panel A) for the three conditions averaged across participants. Error bars are standard errors of the mean.

worse than the one revolution onset, indicating that introducing an explicit cue is not sufficient to completely isolate a temporal event.

To investigate whether working memory load affected performance in our task, we analyzed the trials separately depending on the order of presentation (whether the static disc was presented first or second). If maintaining a representation of duration indeed affected performance in our task, we would expect that sensitivity would depend on the order of presentation. In the trials in which the static disc was presented first, participants had to maintain the duration of the static disc for longer, as these trials included irrelevant motion at the beginning of the second disc that was in motion. We would therefore expect performance to be

worse in these trials. The analysis of our results showed that there was indeed a cost in sensitivity when there was irrelevant motion at the beginning of the second disc. Interestingly, this cost disappeared in the one-revolution onset condition where both discs were only presented for the duration to estimate. These results are in agreement with previous findings showing that nontemporal task demands interfere with time estimation, in both prospective and retrospective tasks (Brown, 1985; Brown, 1995; Brown, 1997; Üstün, Kale, & Çiçek, 2017). Furthermore, it has been shown recently that discrimination of two stimuli is affected by their order and recent history (Nachmias, 2006; Raviv, Ahissar, & Loewenstein, 2012; Raviv, Lieder, Loewenstein, & Ahissar, 2014). More specifically, the

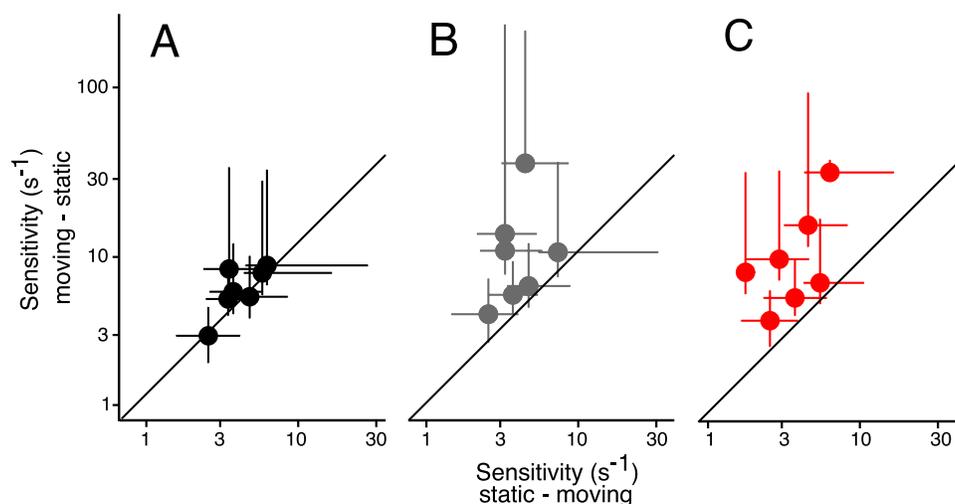


Figure 9. Effect of the order of presentation on sensitivity. Sensitivities (inverse of the standard deviation of fitted psychometric function on a logarithmic scale) for the two orders of presentation are plotted against each other. Each symbol represents one participant in one of the three onset conditions. (A) One revolution onset condition. (B) Cued onset condition. (C) Implicit onset condition. Data for one participant were omitted in the two explicit onset onset conditions (B–C) because it was not possible to obtain reasonable fits with fewer points per stimulus level.

representation of the first stimulus in a trial with two sequentially presented stimuli is affected by past stimuli, and the decision is based on a comparison between the corrupted first and the uncorrupted second stimulus. Extending this finding to our results, we could assume that the noisier the representation, the greater the influence of recent history. Given that the three temporal conditions differ in the amount of uncertainty, the influence of the previous stimuli (which in our experiment converge to the value of the reference) would decrease the difference between the test and the standard to different extents depending on the condition.

## General discussion

In the present study, we investigated the accuracy and precision of temporal judgments when the duration to be estimated does not always have an explicit onset. We designed a novel task and compared performance in this task to that in the classic prospective time estimation paradigm in two separate experiments. We asked participants to track a disc moving on a circular path with varying speeds. When the stimulus stopped, participants had to estimate the duration of the full revolution before the disc stopped moving. We manipulated the explicitness of the onset of the temporal interval in three conditions. The onset was either retrospectively determined to participants (implicit onset, Experiments 1 and 2), or it was known beforehand since the stimulus made only one revolution (one-revolution onset, Experiments 1 and 2), or it was cued by an abrupt brief stopping of the disc (cued onset, Experiment 2). We assessed temporal estimation in two different tasks, either by asking participants to reproduce perceived duration or to compare it to the duration of a static disc.

In both the explicit and implicit onset conditions, we found two classical signatures of time estimation: regression to the mean and scaling of the variability with the estimated duration. These findings are in agreement with previous studies showing similarities between prospective and retrospective timing estimation (Boltz, 2005) and models that assume the same mechanisms for timing in both contexts (Shankar & Howard, 2010; French et al., 2014).

The main difference between the two temporal conditions was the size of the effects. More specifically, we found that the regression to the mean, also known as Vierordt's law, was larger in the implicit onset condition than in the explicit onset condition. Since it has been proposed that Vierordt's law is related to the uncertainty of temporal estimates, the difference between the two conditions could come from differ-

ences in the variability of the temporal estimates (Jazayeri & Shadlen, 2010). In line with this hypothesis, in Experiment 2 we found that sensitivity of temporal discrimination was indeed larger in the one-revolution onset relative to implicit onset condition.

In all conditions of the two experiments, participants were aware that their task was to estimate the duration of the moving stimulus. Therefore, they were always attending to time. We designed the implicit onset experiment in a way to prevent some strategies, such as estimating time from speed (speed changes multiple times within a trial), using landmarks (random stopping position across trials) or counting. In addition, in Experiment 1B, we showed that trials in which stimulus speed changed at the onset of the target were not different from trials in which there was no change of speed (the stimulus was moving with a constant speed for more than one revolution before stopping), suggesting that participants were not using speed changes as a cue.

In a control experiment, we found that participants were not able to reliably detect the onset of the targeted revolution even when they were explicitly asked to do so. We asked five participants who had previously completed the duration reproduction experiment to press a key on a keyboard as soon as they believed that the targeted revolution had started. None of the participants were able to reliably identify the target (hit rates within 20%–40%).

Can we assume that the same mechanism is underlying the performance across the two temporal conditions in spite of differences in variability of estimates? From previous work on visual working memory, we know that prioritization of an item leads to its enhanced recall (Gorgoraptis, Catalao, Bays, & Husain, 2011). Since in the explicit onset conditions the beginning of the revolution to be estimated is explicitly cued, we could assume that it has been memorized with greater precision. Therefore, the same mechanism in both tasks could be underlying temporal estimation (e.g., sampling of decaying activation trace [French et al., 2014] or reconstruction from temporal context vectors [Shankar & Howard, 2010]), while the difference in variability originated from the precision in memorizing the onset of the revolution.

In the second experiment, sensitivity of temporal judgments was affected by the order in which stimuli were presented. In particular, temporal judgments were worse in implicit and cued onset conditions if the static stimulus was presented first. This finding suggests that working memory load, present in both implicit onset and cued onset conditions, affects our ability to compare temporal intervals. The difference in sensitivity could be explained by the effect that past history has on the representation of the first stimulus in the sequence (Raviv et al., 2012; Raviv et al., 2014). It is an

open question, however, whether the effect of memory load on temporal estimation also indicates a close relationship, and possibly a shared neural mechanism between working memory and time estimation, as suggested by previous work (Brown, 1997; Muller & Nobre, 2014; Gu et al., 2015).

To better understand the mechanisms underlying time estimation in our task, it will be pertinent to investigate the parameters affecting performance in explicit and implicit onset conditions. For example, cognitive load has different effects on prospective and retrospective time estimation (Zakay & Block, 2004). Introducing a concurrent task should help us determine if the temporal estimations under uncertainty about the onset of an event require different mechanisms than timing from the beginning to the end of an interval.

One of the limitations of the task we have introduced here is the link between stimulus speed and interval duration. To completely break this relationship, the stimulus would need to travel at nonconstant speeds over parts of the trajectory—for instance, by smoothly accelerating and decelerating throughout the stimulus presentation. Another limitation is that very short durations cannot be tested, although presumably one could reduce the radius of the stimulus path. From the experiments described here, as well as other piloting work, we believe that the present paradigm is best suited for testing temporal estimation of durations in the 1–10-s range.

In the work presented here, we investigated timing in a more natural context, because in real life, we often do not know in advance that a relevant event is about to start. As in our experiment, it is often the case that only when an event is finished do we need to estimate when it started or how long it lasted. Even though our stimuli and tasks are still far from an actual naturalistic context, we believe that they do address one of the key aspects of naturalistic time estimation: the unpredictability of events to be timed.

*Keywords:* temporal estimation, visual duration perception, timing models, retrospective time estimation

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## Supplementary material

Code for presenting the stimuli and data can be downloaded from [https://osf.io/dcbp5/?view\\_only=1e8e938723894c4dbb3642f7cf68c4fc](https://osf.io/dcbp5/?view_only=1e8e938723894c4dbb3642f7cf68c4fc).

**Supplementary Movie S1.** Video illustrating a single trial.